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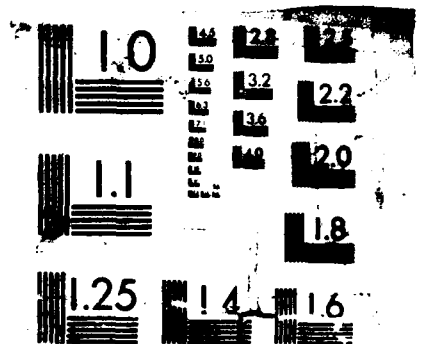
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DOCUMENTATION AND ANALYSIS OF IAEA
SAFEGUARDS IMPLEMENTATION AT THE
EXXON NUCLEAR FUEL FABRICATION PLANT

CONTRACT NUMBER AC1NC108

PREPARED FOR

U.S. ARMS CONTROL AND DISARMAMENT AGENCY

PREPARED BY

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2101 HORN RAPIDS ROAD
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ABSTRACT

The Exxon Nuclear low-enriched uranium fuel fabrication plant in Richland, Washington was the first U.S. bulk handling facility to be selected for IAEA inspection. IAEA inspections were initiated at the Exxon Nuclear plant in March 1981. Those inspections provided the U.S. with an opportunity to gain direct experience in the implementation of IAEA safeguards. Because of the value of that experience to the U.S. in its efforts to assist the development of effective international safeguards, ACDA contracted with the Exxon Nuclear Company to document, analyze and report on implementation of IAEA safeguards at its fuel fabrication plant.

Between March 1981 and November 1983, 12 IAEA inspections were carried out, including three inventory verifications. Inspection activities included verification measurements of flow and inventory items and records audits. The effectiveness and degree of independence of the IAEA's verification measurements increased during the inspection period as additional verification capabilities were put into use by the inspectors. Operational efficiency also increased with experience and as the result of cooperative efforts by the operator and inspector. Those efforts also resulted in the development of innovative approaches for improving effectiveness and minimizing the cost burden. The experience showed that IAEA safeguards could be technically effective, operationally efficient, and not overly burdensome to the plant operator. A cooperative non-adversarial approach was found to be the best approach for success.

The results of the favorable experience gained at the Exxon Nuclear plant were reported to the IAEA's Standing Advisory Group on Safeguards Implementation (SAGSI), a group of Japanese safeguards experts and at the Fifth Annual ESARDA Safeguards Symposium. Valuable experience was also gained for improving the future implementation of IAEA safeguards in the U.S.

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I. INTRODUCTION

For a number of years, the U.S. Arms Control and Disarmament Agency (ACDA) and other agencies of the U.S. Government have been assisting the International Atomic Energy Agency (IAEA) in developing equipment, procedures and methodologies for use by the IAEA in implementing safeguards. However, since IAEA safeguards were being implemented in the U.S. (prior to 1981) on only a very limited basis under an existing tri-lateral safeguards agreement, the U.S. had almost no direct experience in the implementation of IAEA safeguards. Such experience would be invaluable to the U.S. in 1) increasing the effectiveness of its efforts to improve IAEA safeguards, 2) testing evaluation methodologies for measuring safeguards effectiveness, and 3) for the coming implementation of IAEA safeguards in the U.S. under the Presidential offer.

In 1967, President Johnson offered to permit the IAEA to apply its safeguards to peaceful nuclear activities in the U.S. This offer was reaffirmed by Presidents Nixon and Ford. The formal agreement between the U.S. and the IAEA was signed by President Carter on July 31, 1980 and entered into force on December 9, 1980.

On February 17, 1981, the Exxon Nuclear Company was notified that its low-enriched uranium fuel fabrication plant was chosen for inspection by the IAEA under the U.S./IAEA Agreement. As a result, the U.S. now had an opportunity to gain direct experience in the implementation of IAEA safeguards. To assure that this experience was fully documented and communicated to all appropriate agencies of the U.S. Government, ACDA entered into a contract (AC1NC108) with the Exxon Nuclear Company (ENC) to perform a study to document and analyze the IAEA safeguards activities carried out at its fuel fabrication plant.

This report summarizes the work performed under Contract AC1NC108 on the implementation of IAEA safeguards at the ENC fuel fabrication plant during the period of February 27, 1981 through November 8, 1983. The original study which included three specific tasks was later modified to include three additional tasks. The six tasks undertaken in the study are:

1. Task I - Documentation of IAEA Inspection Activities;
2. Task II - Analysis of Inspection Activities;
3. Task III - Documentation of Anomalies and Problems;
4. Task IV - Areas for Safeguards Improvements;
5. Task V - Comparison of Safeguards in Similar Facilities; and
6. Task VI - Reporting on Safeguards Experiences.

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Summaries of the work performed under each of the tasks are presented separately in the subsequent sections of this report. For Task II, Analysis of Inspection Activities, an integration of the results and an analysis of the changes and trends in IAEA inspection activities which took place when the plant was under inspection are presented.

The six task summaries are followed by the Conclusions, Recommendations, References, and Appendices A, B, and C.

II. DOCUMENTATION OF IAEA INSPECTION ACTIVITIES

A. Inspections Carried Out from February 27, 1981 Through November 8, 1983

On February 27, 1981, the Exxon Nuclear Company (ENC) received written notice from the Nuclear Regulatory Commission (NRC) that its low-enriched uranium fuel fabrication plant had been selected for inspection under IAEA safeguards. The letter of notification from NRC requested that Exxon Nuclear submit the book inventory as of February 28, 1981 for the starting inventory under IAEA safeguards.

It was requested orally by NRC and agreed to by Exxon Nuclear that Exxon Nuclear would permit the IAEA, prior to a completed Facility Attachment or other implementing documents, to verify the physical inventory in conjunction with the plant physical inventory taking (PIT) which was scheduled for the end of March 1981. That activity would serve to verify the starting inventory under IAEA safeguards. As a result, the first inspection activity was the verification of the plant physical inventory taken by the operator on March 26 and 27, 1981.

Between the first visit by the IAEA on March 25, 1981 and the last visit which ended on November 8, 1983, there were 12 inspections. The general purpose of each inspection and the number of inspection man-days involved are shown in Table 1. As shown by the data in the table, the inspections were of two general types. These were 1) physical inventory verifications involving 28 to 34 inspection man-days and 2) flow verifications involving 4 to 9 inspection man-days.

B. Verification Measurements

The verification measurement methods used by the IAEA and the items to which they were applied during the inspections of the Exxon Nuclear fuel fabrication plant are shown in Table 2.

The gross weights of UF₆ cylinder were verified using the IAEA's Load Cell Based Weighing System (LCBS).⁽¹⁾

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TABLE 1IAEA INSPECTIONS OF EXXON NUCLEAR FUEL
FABRICATION PLANT

<u>Inspection Number</u>	<u>Date</u>	<u>Inspection Activities</u>	<u>Estimated Man-Days</u>
1	3/25/81 to 4/1/81	Physical Inventory Verification	28
2	5/18-20/81	Flow verification of UF ₆ and rod loading and records audit	9
3	8/12-14/81	Flow verification of UF ₆ , verification of UO ₂ powder measurement, records audit, and discussion of facility attachment	10
4	12/2-4/81	Flow verification of UF ₆ , records audit, and discussion of facility attachment	8
5	1/18-20/82	Flow verification of UF ₆ , verification of the quality of product measurements, and records audit	6
6	4/14-23/82	Physical Inventory Verification	35
7	6/28/82 to 7/2/82	Flow verification of UF ₆ and fuel assemblies, observe rod loading, and records audit	6
8	8/12-16/82	Flow verification of UF ₆ and rod loading station taking pellet samples and using IAEA weights, and records audit	4
9	11/8-9/82	Flow verification of UF ₆ , fuel assemblies, and rod loading station and records audit	4

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TABLE 1 (Continued)

<u>Inspection Number</u>	<u>Date</u>	<u>Inspection Activities</u>	<u>Estimated Man-Days</u>
10	1/12-13/83	Flow verification of UF ₆ , product measurement quality evaluation, and records audit	4
11	3/15-22/83 3/28-29/83	Physical Inventory verification	33
12	11/7-8/83	Records audit and closeout	4

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TABLE 2VERIFICATION METHODS USED BY IAEA AT
EXXON NUCLEAR FUEL FABRICATION PLANT

<u>Item</u>	<u>IAEA Verification Measurements</u>
UF ₆ in Cylinders	Weighing with IAEA load cell system and enrichment by NDA.
Pellets in Boats & Trays	Weighing on operator scales, sampling and U and U-235 assay at IAEA laboratory.
Uranium Oxide Powders	ENC SAM-2 or IAEA B-SAM enrichment meter attribute test, and weighing, sampling and U and U-235 assay at IAEA Laboratory.
Fuel Rods	ENC active rod scanner using standard rods verified by IAEA by destructive measurements.
Fuel Assemblies	IAEA Neutron Collar.
Waste Barrels and Filters	IAEA B-SAM attribute test or operator's passive gamma counter.

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The enrichment of UF_6 was verified with a germanium detector and a multi-channel analyzer by measuring the U-235 gamma rays coming through the side of the cylinder. An ultrasonic thickness gauge was used to measure the wall thickness of the UF_6 cylinder to correct for gamma ray attenuation. The enrichment of UF_6 in selected cylinders was also verified on a limited basis from samples of the first processing vessel in which the UF_6 gas enters the process.

The inspectors verified the weights of containers of fuel pellets by witnessing Exxon Nuclear's re-weighing of them. Pellet samples were also selected for measurement of U and U-235 later at the IAEA laboratory.

For verification of containers of uranium oxides, the inspectors used the Exxon Nuclear SAM-2 enrichment meter with calibration as an attribute test. The selected items were first weighed and then machine tumbled to mix the material prior to the enrichment measurement. The tumbling insured that any substituted inert materials would be detected, since the SAM-2 as used only detects the gamma rays coming from the uranium in the bottom of the container. A fraction of the items was sampled for U and U-235 and analyzed later at the IAEA laboratory. These samples provided the inspectors with the necessary independent standards for use of the operator's SAM-2. They also provided the data for the inspectors' variables test. Independence of the attribute test was preserved by completing the SAM-2 enrichment measurements for the inspectors on all of the items used in the attribute test before any items were selected by the inspectors for sampling.

The nuclear material content of fuel rods was verified using the operator's active rod scanner. Fuel rods randomly selected for verification by the inspectors were measured using the scanner for both total fissile count and enrichment uniformity. The rods were compared on the scanner with the full-length "standard" rods which were selected from the reject or excess fuel rod inventory and matched the rods under test. At the end of the verification with the rod scanner, one or more of the "standard" rods were downloaded by the operator under the surveillance of the inspectors by opening one end and sliding the pellets onto a weighing tray for weight verification and selection of pellet samples by the inspectors. This approach, which is equivalent to a destructive analysis of the standard rods, provided the inspectors with "independent" standards matching the rods verified. The majority of the rods were matched by standard rods and can be considered as measured by a variables method. A smaller number of rods (approximately 20%), not matched with standard rods, can still be considered verified from an attribute standpoint (to within $\pm 10\%$). For those rods not matched by a "standard" rod, an equation was developed from rod assay data which predicts the total fissile counts as a function of the weight of U-235 in the rod and the stated enrichment of the rod.

The fissile density of fuel assemblies was verified using the neutron collar.(2,3)

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For solid waste (contaminated rags, gloves, etc.) in barrels and contaminated HEPA Filters, the IAEA used the portable B-SAM enrichment meter as an attribute test to show the presence of low-enriched uranium. Prior to use of the B-SAM, the operator's passive gamma Waste Assay Counter was used.

C. Typical Inspection Activities

1. Physical Inventory Verification (PIV)

For a typical annual physical inventory verification (PIV), a team of 4 to 6 inspectors were involved over a 6 to 8 day period. One inspector would usually arrive one or two days before the physical inventory taking (PIT) to develop in coordination with the plant operator a schedule for carrying out inventory verification activities and/or to test or calibrate new IAEA measurement equipment. The rest of the inspectors usually arrived the first day of the two day PIT period. This is the day the outside storage areas and ancillary production and research areas were inventoried. The morning of that day was spent by the inspectors in completing verification planning and in setting up, testing and/or calibrating the IAEA NDA equipment. By midday of the first day of the PIT, the itemized inventory lists (copies of the operator's inventory sheets) were available for some of the first areas inventoried during the PIT. These were submitted to the IAEA inspectors as the operator's statement so the IAEA could begin their inventory verification activities; e.g., selecting items for test and performing independent measurements to verify operator's statements of nuclear material content.

On the second day of the PIT (usually a Friday), the main process building and storage area were inventoried. This completed the PIT. The inspectors worked a double shift (day shift and swing shift - 1600 to 2400 hours) on Friday and also some of the inspectors worked on Saturday so as to complete verification activities in the main production areas before production was resumed on the following Monday.

On Monday following the PIT, verification of fuel rods, fuel assemblies and waste items was initiated. After Monday, two of the inspectors usually left and the remaining inspectors completed the verification activities.

On the Tuesday following the PIT, verification of fuel rods, fuel assemblies, and waste items was completed and the records audit started. By the end of Wednesday, the records audit and all verification activities except the packaging of samples were usually completed. By midday Thursday, the samples were usually packaged and ready to ship to Vienna. Thus, the annual PIV was completed within a week of the start of the PIT. That is, the PIT began on Thursday of one week and the inspection part of the PIV was completed on Thursday of the next week.

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2. Interim Inspection (Flow Verification)

The interim inspections which were termed by the inspectors as flow verification usually involved two inspectors for a two or three day period. Those inspections usually involved the verification of the gross weight and enrichment of UF_6 in cylinders, verification of the measurements made at the rod loading station, and/or verification of the fissile density of fuel assemblies with the neutron collar and a records audit.

3. Records Audit

A records audit was usually made during each inspection. Typically, the audits were "book inventory" audits in which the shipments and receipts and the monthly book inventories were compared and cross-checked for each material type. The inspectors compared the source documents, Form 741, or internal forms for shipment and receipts which were too small to report on Form 741 to the Monthly Receipt and Shipment Journals. If time permitted, a 100 percent comparison was made. If not, all larger transfer values and some smaller transfer values were checked. The total receipts and shipments for the month were compared to the monthly Book Inventory Report. The calculations for that report were also double-checked by the inspectors.

D. Logistics

The IAEA equipment including the neutron collar, neutron source, intrinsic germanium detector (crystal, photo-multiplier tube, and Dewar), multi-channel analyzer, ultrasonic thickness gauge, SAM-2 enrichment meter, B-SAM enrichment meter, and standard weights were shipped to the Richland, Washington site by airfreight from either IAEA Headquarters at Vienna, Austria, or the IAEA Field Office at Toronto, Canada. The Load Cell Based Weighing System (LCBS) for weighing UF_6 cylinders was shipped from the Brookhaven National Laboratory at Long Island, New York.

The above equipment and IAEA sample bottles and miscellaneous working items such as a sealed container of IAEA seals were kept in a small storeroom (100 square feet).

The intrinsic germanium detector was cooled with liquid nitrogen by Exxon Nuclear technicians the day before the inspectors were scheduled to arrive. Thus, the system was available for immediate use by the inspectors upon their arrival at plant site. The other equipment, if scheduled for use during an inspection, was transported from the storeroom to the inspector's working office (a Conference Room) so that it was ready for assembly and use by the inspectors. At the completion of the inspection, the equipment was disassembled and placed in its "suitcase" shipping containers and returned to the storeroom.

For each inspection, the inspectors were provided with a working office (an approximate 225 square foot Conference Room) on plant site.

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Customs declarations and bringing the equipment through U.S. Customs in Seattle, Washington, was handled by Exxon Nuclear's Custom House broker in Seattle. This subject is discussed further in Section IV, Documentation of Anomalies and Problems.

E. Charges to the IAEA

For the first Ad Hoc inspection which was prior to completion of the Facility Attachment, an oral agreement was reached with the IAEA on the services to be performed for the IAEA for which charges would be made. For subsequent regular inspections, in accordance with the completed Facility Attachment, the IAEA was charged for the uranium and U-235 in the samples shipped to Vienna, the labor involved in packaging and exporting the samples to Vienna, and the labor and instrument usage for having the operator perform verification measurements for the IAEA on fuel rods with the Exxon Nuclear active rod scanner. The IAEA was also charged for special services such as the cost of shipping the IAEA equipment to other locations in the U.S. and for providing the IAEA with working standards for use at the U.S. Gas Centrifuge Enrichment Plant at Portsmouth, Ohio, and having operators make special measurements or work part of an extra shift to obtain special data.

Total charges to the IAEA for services and materials agreed to under the Facility Attachment for the period the plant was under IAEA inspection (March 1981 to November 1983) amounted to about \$6,100 U.S. dollars. Total charges to the IAEA, including the additional labor charge for the first inspection and all special services and materials, amounted to about \$8,700 U.S. dollars.

III. ANALYSIS OF INSPECTION ACTIVITIES

A. Scope of Analysis

The IAEA inspections of the Exxon Nuclear fuel fabrication plant took place over a two-year period. During that time, changes in the inspection activities took place as experience was gained and as new IAEA measurement equipment was put into use. The changes and trends in inspection activities are important from the standpoints of 1) safeguards effectiveness, 2) operational effectiveness, and 3) cost burden to the operator. This Section presents an analysis of the changes and trends in inspection activities which took place during the years the plant was under inspection. They are discussed separately next for each of the three standpoints noted above.

B. Safeguards Effectiveness

1. Basis of Evaluation

Because of the nature of safeguards arrangements under which IAEA safeguards were applied under the U.S./IAEA Agreement, the effectiveness of inspection activities was evaluated on a separate basis for each type of verification - inventory verification and flow verification. For physical

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inventory verification, the effectiveness of inspection activities was evaluated on the extent to which the IAEA was able to verify operator statements of inventory quantities on the basis of the operator providing an itemized list of the inventory items and the U and U-235 content of each item. In this case, effectiveness can be based on the ability of the IAEA to verify by use of fractional sampling plans the total number of items in a stratum as well as the U and U-235 content of individual items.

For flow verification, it was not possible under the planned inspection frequencies and other arrangements for implementing safeguards in the U.S. for the IAEA to establish independently the population of flow items. Thus, the evaluation of the effectiveness of flow verification was based on the ability of the IAEA to verify the stated U and U-235 content of individual flow items such as UF₆ cylinders and fuel assemblies.

2. Physical Inventory Verification

The quantitative objective of the IAEA was to verify the operator's statement of total inventory quantities to the extent that the absence of a goal quantity of nuclear material would be detected with a probability of 0.95. The goal quantity used for the first two inventory verifications (March 1981 and April 1982) was 75 kilograms of contained U-235 which is one significant quantity (SQ) of low-enriched uranium for purposes of international safeguards. For the last inventory verification in March of 1983, a slightly larger value was used which is based on the concept of the Verification Accuracy Limit (VAL). This limit is defined as the percentage of the largest of throughput or inventory which, if lost, can be detected with a high probability with a measurement system that meets international standards of accountancy.

For inventory verification, an attributes-variables sampling plan was used to select items for verification by "independent" measurement. That plan is designed to detect with high probability the absence of a goal quantity whether it has been removed by taking a small number of whole items, by partially taking material from many items, or by taking a small amount of material from a large number of items.

For inventory verification, the inspectors usually used the following formula to compute their attribute (detect large defects) sample size for a stratum:

$$n_a = N \left[1 - (0.05)^{\frac{\bar{X}}{75000}} \right]$$

Where: n_a is the number of samples for the attribute test;

0.05 is probability of not including at least one defect in the sample if a goal quantity were taken as whole items.

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For the variables sample size for detecting small biases and medium-sized defects (up to 20 percent missing from an item), the following formula was used:

$$n_{v1} = N \left[1 - (0.05) \frac{0.2 \bar{X}}{75000} \right]$$

Where:

n_{v1} is the number of samples to be tested by the variable method used in the attribute mode and the number of samples to also be tested using the variables method in the variables mode;

N is the number of items in the stratum;

\bar{X} is the average amount of U-235 in an item in grams;

75000 is the goal quantity in grams of U-235;

0.05 is the probability of not including at least one defect if a goal quantity were taken by removing 20 percent from individual items; and

0.2 is the fraction of material missing from an item which can still be detected with high probability by the attribute method. However, if less than this fraction is missing (less than 20%), it is assumed that it will not be detected by the attribute method but by the variables method used in the attribute mode.

For all inventory verifications, the inspectors did take sufficient samples from most strata to meet their verification goals. There were two principal exceptions. The sample size for the attribute test for UF₆ cylinders (81% of the items) was only approached at the last inventory verification (March 1983) when the portable B-SAM enrichment meter was available for use. Also, the attribute sample size for fuel assemblies (21% for BWR assemblies and 45% for PWR assemblies) was only approached at the last inventory verification when neutron collar measurements were made on seven assemblies.

The most important trend in effectiveness which took place during the inspection period was the increase in the independence and detection capability of IAEA verification measurements with the introduction of new or additional equipment. This included the load cell weighing device for UF₆ cylinders, the neutron collar, the portable B-SAM enrichment meter, and the IAEA standard weights.

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The power of IAEA verification measurements to detect an inventory bias was estimated from a combination of technical analysis and experience data for operator-inspector differences for measurements made on the same item or same sample of material. The results are shown in Table 3 assuming an inventory composition which might be typical of a medium sized LEU fuel fabrication plant. The measurement uncertainties shown by the D_i statistic for the first four rows are based on typical sample sizes for IAEA inventory verifications and paired comparison data. The values for liquid and solid waste are based on a technical analysis of measurement considerations for verifying the amount of solid and liquid waste accumulated during an annual accounting period. Because of the limited experience data on use of the neutron collar, example errors are used to illustrate the potential impact that fuel bundle verification can have on the overall verification process.

The data in Table 3 illustrate the good power to detect bias for items which can be verified by weighing, sampling, and destructive analysis. The content of fuel rods can also be verified to a good degree of exactness by a combination of active rod scanning and destructive analysis and weighing of the pellets "downloaded" from the standard rods.

By contrast, only relatively large biases can be detected in regard to the content of fuel bundles, UF_6 cylinders, and solid and liquid wastes. However for the assumed inventory composition, the overall power of bias detection by the combination of NDA and destructive analysis (including weighing) is quite good. For example, an inventory overstatement of 0.7 percent would be detected 95 percent of the time.

The main weakness with the initial inventory verification was the degree of dependence of the inspector's measurements on the operator's systems. Weight verification was by having the operator reweigh items using his scales and standard weights. Solid waste items were verified by remeasurement by the operator on his Waste Assay Counter. Fuel rods were verified using the operator's rod scanner and uranium oxide powder containers were tested for enrichment with the operator's SAM-2 enrichment meter. This lack of independence was recognized by the IAEA and two methods for increasing the degree of independence were developed in cooperation with the plant operator. A procedure was developed for taking destructive samples from uranium oxide containers that increased the independence of the use of operator's SAM-2 enrichment meter (see Section II B). The degree of independence for use of the operator's rod scanner for fuel rod verification was increased by the introduction of full length rod standards which could be verified by the inspectors by destructive measurements (see Section II B).

3. Flow Verification

The effectiveness of flow verification was judged from the standpoint of the inspector's ability to verify the content of the items which comprised main input and output flows - cylinders of UF_6 and fuel assemblies. Most wastes were retained onsite and were verified as part of the inventory.

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TABLE 3
APPROXIMATE POWER OF IAEA VERIFICATION MEASUREMENTS
TO DETECT INVENTORY BIAS AT EXAMPLE FUEL FABRICATION PLANT

Stratum	Inventory Quantities		$\hat{\phi}$		$3.29\sigma \hat{D}_i$	
	Kgs, U	Kgs, U-235	U% (4)	U-235% (4)	U, Kgs	U-235, Kgs
UF ₆ (1)	2,000	84	11.5	11.5	322	9.66
UO _x Powder	100,000	3,000	0.473	0.554	473	16.62
Sintered Pellets	50,000	1,500	0.209	0.459	104.5	6.89
Fuel Rods	25,000	750	0.865	0.865	216.3	6.49
Fuel Bundles (2)	10,000	300	10.55	10.55	10.55	31.65
Liquid Waste (3)	500	15	40	40	200	6.00
Solid Waste (3)	500	15	40	32.9	200	4.94
TOTALS	188,800	5,664	0.665	0.689	1256.24	39.00

- (1) Open UF₆ cylinders verified by weighing and NDA enrichment measurement. Unopened UF₆ cylinders are assumed to be under IAEA seal from verification at enrichment plant.
- (2) Unpackaged fuel bundles measured by neutron collar. Assumed systematic error is three (3) percent and assumed random error is three (3) percent at the one sigma level.
- (3) Wastes are assumed to represent a one year accumulation.
- (4) Relative percent error in total U and total U-235 at the 3.29 σ level for the difference statistic for a stratum (\hat{D}_i). It includes all errors making up total, e.g., for total U-235 in UO_x powder it includes weighing, sampling, U-assay and U-235 assay errors.

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For verification of UF₆ in cylinders, the same intrinsic germanium detector and kind of multichannel analyzer were used for the entire period. Other than becoming more proficient in making the enrichment measurement and in establishing a larger data base, there was not a significant change in the accuracy of the enrichment measurement. However, for the weight verification a major change took place when the load-cell weighing device for UF₆ cylinders was introduced. This device provided the IAEA with an independent means to weigh cylinders with an accuracy approaching the plant weighing system.

For fuel assemblies, the inspectors did not bring the neutron collar to the plant until the summer of 1982. This instrument provided the inspector with a direct means of measuring the fissile density of a full cross-section of a fuel assembly. The use of the collar closed a major gap in the inspectors verification of both flow and inventory. It should be noted that the above discussion of the increase of safeguards effectiveness for verification of either input or output flow applies only to the verification of the content of an item selected for test not the population of items comprising the flow.

C. Operational Efficiency

As experience was gained by both the inspectors and plant personnel in carrying out the verification measurements and records audits, the efficiency of the inspection activities increased. As a result, it was possible to complete more measurements and audit more transactions in a given period of time.

After the first several inspections, it was possible for the inspectors and plant safeguards personnel to anticipate each other needs so that arrangements for measurements, calibration standards, equipment setups, source data, and records could be made prior to the arrival of the inspectors. Thus, for many of the interim inspections, it was possible for the inspectors to proceed directly with their verification activities soon after arrival at the plant. Patterns were also established for quickly assembling (or preassembling) and disassembling the equipment and for quickly removing the equipment from storage and returning it to storage at the end of the inspection. It was also possible to gather some of the source data for the interim inspections prior to the arrival of the inspectors.

For the records audits, copies of the monthly Receipts and Shipment Journals and the monthly Book Inventory Report were prepared before arrival of the inspectors. In addition, a special monthly transaction listing was prepared showing the beginning book inventory, ICR transactions and the ending book inventory.

A significant increase in operational efficiency for inventory verification resulted from cooperative efforts of the inspectors and plant safeguards personnel. Those efforts included the cooperative development of

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an inventory verification plan and schedule several weeks or a month before the PIT and PIV. This allowed the operator to schedule personnel for preparing the itemized inventory lists (copies of the inventory taking data sheets), for locating, moving, and measuring items for the inspectors during the PIV at each area, and for escorting inspectors and U.S. Government personnel, if in attendance. The PIV plan provided both the inspectors and Plant Operations with a working schedule so that there was little lost time between completing the PIT for an area and starting the PIV.

D. Cost Burden to the Operator

There are two principal concerns of plant operators regarding the potential cost burden of inspection activities. The first and main concern is the potential for inspection activities to slow, halt, or delay production. The second concern is for potential direct "out of pockets" costs arising from inspection activities such as having to pay overtime hours to perform measurements requested by the IAEA.

Because of the potential for lost production, inventory verification was of most concern from the standpoint of cost burden. The interim inspections (or flow verifications) had little impact on production.

Because of the importance of cost-effectiveness in establishing widely acceptable safeguards, a special cooperative effort was undertaken to develop a cost-effective approach to inventory verification. Two specific objectives had to be attained. First, for the inspectors' verification to be valid, they needed an itemized list of the inventory prior to starting their verification activities. However, the operator could only supply such a list by first completing the PIT. Second, the time between when the operator completes his PIT and when production is allowed to resume upon completion of the PIV must be minimized.

As a result of the above considerations, the approach described next was developed and used for the last two inventory verifications (April 1982 and March 1983). Shortly after the physical inventory taking (PIT) was completed for each area, copies of the operator's itemized inventory taking data sheets were made and given to the inspectors. They then used those sheets to select their random samples and carry out their verification measurements for the inventory area. To minimize lost production time, the inventory of the main process areas was taken on a Friday before the normal weekend break in production. In conjunction with this schedule, the inspectors then worked two shifts on Friday (day shift and the evening shift, 1600-2400 hours) and also on Saturday to complete their verification activities while most of the process was in a shutdown mode. In cases where production was resumed on Friday evening, the inspectors completed verification of a portion of the inventory in the area, e.g., material in the rod loading hoods, so that production could resume for the Friday evening shift.

The addition of the portable B-SAM enrichment meter for the last inventory verification (March 1983), did reduce the cost-burden of that acti-

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vity. Prior to the March 1983 inventory verification, the operator had introduced the use of a larger, critically safe container for uranium oxide powder. Those containers of 500 kilograms in weight were stored on tiered shelves in the powder storage facility. To verify the enrichment of the UO_2 in those containers by the normal method of using the operators fixed-position SAM-2 enrichment meter, would have taken an additional 8-16 hours of verification time. However, with the availability of the portable B-SAM, it was possible to do the enrichment verification by moving the inspector and B-SAM to each container rather than move the containers to the fixed-positioned SAM-2.

IV. DOCUMENTATION OF ANOMALIES AND PROBLEMS

A. Safeguards Anomalies and Problems

During the inspection period, there were four main anomalies or problems of a safeguards nature. These are described briefly below.

1. Item Count Discrepancy

The first anomaly concerned the inspector's item count of scrap containers in the warehouse during the first inspection in March of 1981. The inspector reported that he found 57 fewer scrap containers than stated by the operator. The problem was quickly resolved by having the full inspection team as well as U.S. government personnel and plant safeguards personnel do an item count of the warehouse. The 57 containers were found stored along one wall in established floor grid positions. The inspector had not been instructed that the 57 containers in the floor grids were part of the stated total for that stratum.

2. Submittal of Itemized Inventory List

The second problem of a safeguards nature also occurred during the first inspection. To carry out their verification of the inventory, the inspectors requested an itemized listing of the inventory. They indicated that this was to be given directly to them rather than submitted through the U.S. government as plant personnel had thought was necessary. So that the verification could proceed, the inspectors were provided with copies of the operator's inventory taking data sheets. These were provided on a provisional basis with the final version being the Physical Inventory Listing (PIL) which was to be submitted later through the U.S. government.

However, it was soon apparent that the PIL would not provide the inspectors with the final itemized listing they needed since the PIL was a summary not an itemized listing. The inspectors needed the final itemized listing which summed to the plant inventory to check the original data sheets to assure that item values had not been changed. Thus, to provide the inspectors with a valid basis for the verification, a final itemized inventory listing which summed to the total inventory for each material type was sent directly to the inspectors at Vienna. This was done for all three inventory

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verifications. The itemized listing was either sent as "hard copy" or on a computer tape that could be used by the IAEA.

3. Reporting Problems

The third problem of a safeguards nature concerned the problem of matching transmittals from the plant through the U.S. Nuclear Materials Management and Safeguards System (NMMSS) to the IAEA. Although it was possible for the inspectors to have a self-consistent set of records and reports by using only plant information, it was not possible to match the plant reports with the reports sent to the IAEA via NMMSS.

To resolve the problem, a three day meeting was held in June 1982 at the NMMSS offices at Oak Ridge, Tennessee. In attendance were U.S. information specialists and the Nuclear Materials Accountant for ENC. A line by line comparison was made between ENC shipment and receipt records with NMMSS receipt and shipment records and the differences were identified. From this exercise, it was apparent that each facility under IAEA safeguards should, in addition to the reports submitted for individual transactions, prepare a monthly ICR listing showing each transaction, and beginning and ending book inventories. The ENC plant adopted this procedure and routinely sends to NMMSS a manual ICR transaction report.

Another problem identified at the June 1982 meeting was the problem of batch reporting on fuel shipments. The U.S. system requires a summary by enrichment and by country of origin whereas the IAEA requires the reporting of each assembly as one batch. To resolve this problem, ENC developed two separate formats to meet both U.S. and IAEA reporting requirements.

A more long range solution to the problem may be to have the U.S. facilities under IAEA reporting requirements report their IAEA related transactions (ICR, MBR, PIL) in two formats. One format to meet IAEA requirements and the other format to meet U.S. requirements.

4. Liquid Waste Verification

The fourth problem concerned the results of the liquid phase samples of the lagoons which were taken during the April 1982 inventory verification. The inspectors expressed concern when their verification results were lower than the stated total lagoon inventory. When it was explained to the inspectors that the total lagoon inventory (which represented an accumulation of many years) also included a good fraction of uranium bearing solids which were not represented by their liquid phase samples, they appeared to be satisfied. However, during the March 1983 inventory verification, the same concerns were expressed again. As a result, a special presentation and data sheets were prepared for the inspectors. Those data sheets showed the estimated solid and liquid phase totals of the lagoon system inventory on April 1982 and the results of the check samples using both ENC and IAEA analytical values for uranium and U-235. When the data were reexamined in light of the

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analytical differences and the quantities of uranium in solids, it was evident that the April 1982 check sample results did indeed provide a good substantiation of the operator's lagoon inventory.

In the discussion on waste verification, it was recognized that the verification of total stored waste accumulated over a number of years was a different safeguards objective than the verification of statements of annual or semi-annual waste discards.

B. Logistics Problem on U.S. Customs Clearance of IAEA Equipment

Initially all IAEA equipment was brought through customs in Seattle on the basis that the material was an ordinary import and subject to full duty or equivalent treatment. Statements by ENC or the IAEA did not alter that customs status. All IAEA equipment used at the plant in Richland, Washington was brought in initially under either a Temporary Import Bond (TIB), by paying duty, or by declaring or certifying that the IAEA equipment was really U.S. goods being returned to the U.S.

Later, it was learned through the NRC Region V Office that there is an old customs regulation which exempts the IAEA from customs requirements. This was confirmed with the Customs Entry Officer for San Francisco. Customs Regulation, 148.87 entitled, "Officers and Employees of, and Representatives to Public International Organizations" (1945), exempts the baggage and effects of officers and employees from duty. The IAEA was put on this list of approved Public International Organizations in 1957.

This information was sent to the U.S. State Department to see if it could be used as a general basis for bringing in IAEA safeguards verification equipment.

That customs regulation was later used by ENC's Custom House broker in Seattle to obtain relief from U.S. Customs in Seattle for previous Temporary Import Bond (TIB) requirements and also to recover a previous payment of duty made to bring in IAEA equipment.

V. AREAS FOR SAFEGUARDS IMPROVEMENTS

Three areas for safeguards improvements were identified during the course of inspections. These were 1) improving the operability of the load cell weighing system, 2) improving the verification of fuel rods for rods not matched by a standard rod, and 3) improving the basis for handling nonmeasurement errors which impact on the material balance and on inspection planning. These are discussed separately next.

A. Load Cell Weighing Device for UF₆ Cylinders

The operability of the Load Cell Based Weighing System (LCBS) which was used by the inspector to weigh UF₆ cylinders was tested by weighing

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a number of cylinders at different locations at the storage area. This activity simulated an IAEA flow or inventory verification. The arrangement which required extension cords and a separate 12 foot cable for the display box proved to be cumbersome and involved a tedious process of moving the apparatus from one cylinder to another. To use the initial arrangement for verification, required either two inspectors or one inspector and one operator technician. A better arrangement would be to put the display box, calibration box and load-cell into a single unit. An improved compact design was prepared. Those drawings and recommendations were submitted to the person at the Brookhaven National Laboratory who was responsible for the original development of the system for his use in improving the system.

B. Development of Fuel Rod Scanner Prediction Equations

During the April 1982 IAEA physical inventory verification, the IAEA requested that we investigate the possibility of developing mathematical equations to describe the response of the Exxon Nuclear fuel rod active assay machine. The development of such equations would be of importance to the inspectors by allowing them to use the formula as an attributes check for those rods which are not matched by the "standard" rods. Those "standard" rods were downloaded for Agency weight verification and destructive analysis.

The IAEA was initially provided with a copy of a 1975 Exxon Nuclear study in which isobars were developed for four specific rod types. Since the usual mode of IAEA inspections involves measuring different fuel rod types, the use of a different formula for each rod type was impractical. Instead, a single equation for all rod types was desired.

To determine whether such a general equation could be derived, rod scanner measurements data were accumulated for the broad spectrum of standard fuel rods manufactured by Exxon Nuclear, including rods of different length and diameter, BWR and PWR rods, rods varying in enrichment from 0.7% to 4.2% U-235, and multienrichment rods. To further strengthen the data sets, averages of multiple measurements were used to characterize each rod type where possible.

For assembled data, the following mathematical model was used:

$$y = a(1 - e^{bx})e^{cz}$$

where: x = rod U-235 weight
 y = net assay count
 z = rod enrichment
 a,b,c = constants

The equation is similar to the equation for a single rod type, the main difference being the addition of a third independent variable "z", replacing the rod type dependent variable. To correct for the effect of diminished source strength resulting from Cf-252 decay, all values of the variable "y" were normalized to a standard reference date. For this study,

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the date used was March 31, 1981, corresponding to the first Agency use of our rod scanner during the March 1981 Ad Hoc physical inventory verification.

Finally, the values for the constants a, b, and c in equation (2) were determined for each data set by least squares regression. The final fitted equations are as follows:

$$\text{Dual Channel Assay: } y = 947,118(1 - e^{-.0039093x})e^{-.059482z} \quad (3)$$

$$\text{Single Channel Assay: } y = 833,698(1 - e^{-.0039075x})e^{-.057822z} \quad (4)$$

These equations describe the scanner net assay response to 1.5% relative on the average, thus providing the IAEA with an excellent attribute check for the fuel rod strata.

A description of the method, data, and derived mathematical equations was sent to the IAEA rod scanner specialist on July 8, 1982.

In December 1982, the californium-252 source was changed and new equations were developed for 10 rod types for the March 1983 inventory verification. The new equations were sent to the IAEA prior to the March 1983 inventory verification. To make it easier to develop such equations for use at facilities, a computer program was written in BASIC to solve the equation parameters from a facility's rod scanner data. The program was sent to the IAEA rod scanner specialist.

C. Application of Statistical Techniques to Account for Non-Measurement Errors

Statistical techniques were adapted to address the problem of non-measurement errors, e.g., transcription errors, as they affect the material balance and impact on inspection planning. The work is described in a topical report by J. L. Jaech entitled, "Effects of Nonmeasurement Errors on an LEU Fuel Fabrication Facility Material Balance." That report is included as Appendix C.

VI. COMPARISON OF SAFEGUARDS IN SIMILAR FACILITIES

Visits were made to two similar low-enriched fabrication plants in Europe to learn how IAEA safeguards were being implemented in those plants. The first visit was to the Exxon Nuclear GmbH low enriched uranium fuel assembly plant in Lingen, Federal Republic of Germany. The second visit was to the ASEA-ATOM's fuel fabrication plant in Vasteras, Sweden.

The safeguards specialists for those plants were interviewed by R. Nilson of ENC using a prepared questionnaire. From that information, draft reports were prepared for each facility and reviewed by the safeguards specialists. After review of the draft reports, the safeguards specialists

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for each plant agreed to coauthor with R. Nilson of ENC a report on the implementation of IAEA safeguards at those plants. Those reports which are included as appendices are:

1. Appendix A, IAEA Safeguards at Similar Facilities, Exxon Nuclear GmbH LEU Fuel Assembly Plant in Lingen, Federal Republic of Germany," by K. Rodat of Exxon Nuclear GmbH, Lingen, Federal Republic of Germany and R. Nilson of Exxon Nuclear Company, Inc., Richland, Washington, U.S.A.; and
2. Appendix B, IAEA Safeguards at Similar Facilities, ASEA-ATOM LEU Fuel Fabrication Plant in Vasteras, Sweden, by V. Andersson of ASEA-ATOM, Vasteras, Sweden and R. Nilson of Exxon Nuclear Company, Inc., Richland, Washington, U.S.A.

VII. REPORTING ON SAFEGUARDS EXPERIENCES

Work under this task involved the three main activities described separately below.

A. Presentation at the ESARDA Safeguards Symposium at Versailles, France

A paper on the Implementation on IAEA Safeguards at the Exxon Plant was prepared in cooperation with the IAEA inspectors. The paper entitled, "Implementation of IAEA Safeguards at a U.S. Fuel Fabrication Plant," by R. A. Schneider, R. Nilson and E. R. Herz of the Exxon Nuclear Company, Inc. Richland, Washington, U.S.A. in consultation with M. Ferraris, H. Gonzalez-Montes, and W. Theis of the International Atomic Energy Agency, Vienna, Austria was presented at the Fifth Annual ESARDA Safeguards Symposium at Versailles, France on April 21, 1983.

The important conclusions of the paper are given below in a copy of the abstract. Thirty copies of the paper were submitted previously.

ABSTRACT

The Exxon Nuclear low-enriched fuel fabrication plant in Richland, Washington was the first U.S. bulk handling facility chosen for IAEA inspection. Since the first "Ad Hoc" inspection of March 1981, intermittent inspections have been carried out. Inspection activities have included verification measurements of flow and inventory items, measurement quality evaluation, and records audits. Based on the experience gained to date, an assessment has been made of the operational and technical effectiveness of the verification measurement activities. The assessment of operational efficiency and cost burden was made by the plant operator whereas the assessment of goal achievement was made

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by the inspectors. Two important conclusions can be made at this time. First, IAEA safeguards in a low-enriched fuel fabrication plant need not be overly burdensome to the plant operator. Second, the verification measurement activities are operationally efficient and technically effective. These results derive from the cumulative efforts of many and the progress made over a number of years. A paramount reason for the above results can also be attributed to good communication between inspectors and the plant operator. A cooperative non-adversarial approach has been found to offer the best chance of minimizing the burden, improving efficiency, yet maintaining the necessary effectiveness.

The paper is included in the proceedings of the meeting, "Fifth Annual Symposium on Safeguards and Nuclear Material Management," ESARDA 16. Copies are available from the ESARDA Symposium Secretariat, Joint Research Center 1-21020 Ispra (VA), Italy.

B. Presentation to a Group of Japanese Safeguards Experts

On July 12, 1983, a technical presentation, a plant tour, and a measurement demonstration were given to a group of Japanese safeguards experts. The purpose of the presentations was to illustrate how the IAEA carried out their verification measurements and related inspection activities in verifying operator statements of physical inventory quantities. The presentations illustrated the inspection activities and equipment used by the IAEA in inventory verification. The exercise also showed how the IAEA was able to achieve safeguards effectiveness in an efficient manner, yet with a minimum disruption of plant operation.

C. Presentations to IAEA Safeguards Advisory Group (SAGSI)

On April 5-6, 1984, special safeguards presentations were made to the IAEA's Standing Advisory Group on Safeguards Implementation (SAGSI). The purpose of the presentations was to describe and illustrate the safeguards activities carried out by the IAEA at the Exxon Nuclear Fuel Fabrication Plant at Richland, Washington during the time (February 1981 -October 1983) the plant was under IAEA inspection.

During the morning and early afternoon of April 5th, presentations were made at the SAGSI meeting room in the Rivershore Motel at Richland, Washington. The safeguards approach and associated inspection activities were described by W. Theis of the IAEA. The inspection activities were illustrated using actual examples including operator records, ledger books, inventory sheets, source data, and reports. The plant layout and operator's measurement and accounting system were described by R. A. Schneider of Exxon Nuclear.

Those presentations were followed in the late afternoon by a plant tour to show the key measurement points, main process features, and operator measurement equipment. The tour included two demonstrations of IAEA verification activities. The first was a demonstration of rod downloading. The

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operator's fuel rods which are used by the IAEA as "standard" rods when the operator's active rod scanner is used for fuel rod verification are downloaded by cutting open one end and removing all the pellets for verification of pellet column weight and sampling of pellets for destructive assay at the IAEA Laboratory. The second was a demonstration of how the enrichment of uranium oxide powders was verified by the IAEA at the powder storage facility. This was done using a portable enrichment meter. The inspector with the portable meter stood in the "cage" of the mechanical hoist and was lifted to the various storage levels and container locations so he could measure selected containers.

The morning of April 6th was devoted to an onsite demonstration of the various verification measurements which were used by the IAEA to verify operator statements of material quantities. IAEA inspectors W. Theis and P. Ikononou illustrated the use of the IAEA equipment using actual items such as a fuel assembly, UF₆ cylinder, etc. The use of operator measurement equipment was illustrated by plant personnel. The measurement demonstration included UF₆ cylinder weighing with the IAEA load-cell system, enrichment measurement of UF₆ in cylinders with the IAEA NDA system, and the fissile density of a section of a fuel bundle with the IAEA's neutron collar. Other measurements illustrated as part of the IAEA's verification activity included pellet sampling, pellet column weighing, rod scanning, use of the operator's SAM-2 enrichment meter, powder sampling, and weighing of powder buckets and barrels. The onsite demonstrations concluded with a question and answer period.

VII. CONCLUSIONS

The Exxon Nuclear fuel fabrication plant in the U.S. came under IAEA safeguards at a point in time when the capabilities developed over the years for verifying operator statements of material quantities were first beginning to be fully implemented. As a result, a significant increase in the effectiveness and degree of independence of the IAEA verification measurements took place as additional verification capabilities were put into use by the IAEA at the Exxon Plant. These included introduction of 1) the load cell device for weighing UF₆ cylinders, 2) the neutron collar for verifying the nuclear material content of fuel assemblies, 3) IAEA standard weights, and 4) the portable B-SAM enrichment meter. Also, contributing to this increase in effectiveness of verification measurements was the development by the IAEA inspectors and operator personnel of the use of the operator's active rod scanner for fuel rod verification using full length rods as standards which could be verified by the IAEA by destructive measurements.

A similar increase in operational efficiency resulted from the experience gained during the initial inspections and a cooperative effort by the inspectors and operator personnel. Operational patterns and pre-inspection activities were developed which improved the IAEA's operational efficiency in setting-up NDA equipment and in performing NDA measurements and records audits.

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As a result of a similar cooperative effort, an approach was developed which minimized the potential impact of physical inventory verification on production. The inventory was taken just before a normal production break (weekend) so that inventory verification could be done while the process was in a shutdown mode. This approach which required the IAEA inspectors to work a double shift and also on the weekend minimized the potential for lost production. With this minimization of lost production time, it was estimated that the cost burden to the operator of IAEA safeguards amounted to only about one tenth of one percent of fuel fabrication costs⁽⁴⁾.

Studies were carried out in cooperation with the safeguards specialists of two similar low enriched uranium fuel fabrication plants in Europe to determine how IAEA safeguards were being implemented at those plants. From those studies, it was concluded that the verification activities carried out at the plants in Europe were very similar to those carried out at the Exxon Nuclear plant in the U.S.

Three areas for safeguards improvements were studied under the contract. These included 1) improving the operability of the load cell based weighing device for UF₆ cylinders, 2) the development of prediction equations for the active rod scanner which cover the population of different type rods in the inventory, and 3) adapting statistical techniques to address the problem of nonmeasurement errors as they affect the material balance and inspection planning. Of the three improvements, only the prediction equations for the rod scanner were available for use by the IAEA inspectors during the inspection of the Exxon Nuclear plant. The statistical techniques for handling nonmeasurement errors and the design for the improved operability of the weighing device for UF₆ cylinders are available for future use.

Presentations were made to a group of Japanese safeguards experts, to the IAEA's Standing Advisory Group on Safeguards Implementation (SAGSI), and at the Fifth Annual ESARDA Symposium on Safeguards and Nuclear Materials Management at Versailles, France. Those presentations illustrated how cost-effective and operationally efficient international safeguards could be implemented at a plant like the Exxon Nuclear fuel fabrication plant. A cooperative, non-adversarial approach was found to be a main contributor to success.

The experience gained in the implementation of IAEA safeguards at the Exxon Nuclear plant will be useful in implementing international safeguards at other U.S. plants. Some important lessons were learned. These include learning of the existence of U.S. Customs Regulation 148.87 (year 1945) which in effect exempts IAEA verification equipment from duty. Also, it was found that a dual reporting format may be the most practical solution to meeting both U.S. and IAEA reporting requirements. Under this approach, U.S. plants under IAEA reporting requirements would report inventory changes under one format to meet IAEA requirements and under another format to meet U.S. needs.

In addition, during the first inspection which was an inventory verification, it was realized that an itemized inventory listing giving the identity and U and U-235 content of each item must be provided to the IAEA before they

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can validly carry out their inventory verification activities. Such a list cannot usually be provided until the operator has completed his inventory taking and then only a provisional listing can be provided immediately. To solve this apparent dilemma, the IAEA inspectors were provided with copies of the operator's inventory taking data sheets as soon as inventory taking was completed for each area. These were provided on a provisional basis and followed later by a final itemized listing which summed to the operator's final ending inventory. It was also realized that the Physical Inventory Listing (PIL) cannot serve as an itemized listing since it is a summary of batches and number of items in a batch. The best final itemized listing was found to be the detail report from which the PIL is prepared. That report lists each item within each batch giving the identity and contents.

IX. RECOMMENDATIONS

The following recommendations are based on the conclusions of the previous section:

1. That work be undertaken to implement the results of the work on safeguards improvements. This includes 1) applying the improved equipment design in fabricating a compact load cell system for weighing UF₆ cylinders, 2) applying the work on the rod scanner prediction equations at other inspections of LEU fuel fabrication plants, and 3) applying the statistical techniques for handling nonmeasurement errors to actual inspection situations;
2. That serious consideration be given by the U.S. to establishing a separate reporting format for U.S. plants under IAEA reporting requirements as well as a small separate information system for accumulating and transmitting the required safeguards data to the IAEA; and
3. That the arrangement for providing the IAEA with an itemized inventory list as a prerequisite for their verification of the operator's statement of inventory holdings be further explored. If the approach of the operator providing at the time of the PIT a provisional listing which is followed later by a final itemized list submitted through the State is acceptable, then modification should be considered. Modification should be considered from the standpoint of supplementing the PIL with the itemized detail report from which the PIL is prepared.

X. REFERENCES

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APPENDIX A

IAEA SAFEGUARDS AT SIMILAR FACILITIES

EXXON NUCLEAR GmbH LEU FUEL

ASSEMBLY PLANT IN LINGEN, FEDERAL REPUBLIC OF GERMANY

By

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APPENDIX A

IAEA SAFEGUARDS AT SIMILAR FACILITIES

EXXON NUCLEAR GmbH LEU FUEL

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Introduction

The purpose of this report is to describe the implementation of IAEA safeguards at the ENGmbH low enriched uranium fuel assembly plant in Lingen, West Germany.

The plant is a small LEU fuel assembly plant which assembles both PWR and BWR fuel assemblies for delivery to Exxon Nuclear customers in Europe. The plant receives finished fuel pellets from the Exxon Nuclear fuel fabrication plant in Richland, Washington. The pellets are loaded in fuel rods which are then assembled into fuel bundles.

The plant inventory consists almost entirely of fuel pellets present on trays or in shipping boxes, fuel rods, and fuel assemblies. Small quantities are present in the form of pellet scrap and U_3O_8 from the Analytical Laboratory. The plant has no liquid waste and very little solid waste (barrels of contaminated paper, filters, etc.).

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The plant measurement system includes scales for weighing pellet boxes, pellet trays, and fuel pellet columns (rod loading); a passive gamma counter for the nondestructive assay of waste barrels and filters; analytical capabilities for verifying the pellet percent uranium (gravimetric) and a laboratory SAM-2 enrichment meter for verifying the enrichment of fuel pellets. The basic accountability measurements for uranium element (gravimetric assay) and for U-235 (mass spectrometer) are made at the Richland plant. The Lingen plant has a new "best state-of-the-art" active rod scanner for enrichment control.

Inspection

At Lingen in West Germany, the inspections are carried out jointly by the Euratom and the IAEA inspectors. Euratom inspectors appear to play the dominant role. The IAEA inspectors largely observe and witness the work of the Euratom inspectors. The IAEA inspectors are always accompanied by the Euratom inspectors. German law requires the Euratom inspectors to be present with IAEA inspectors unless the plant is notified by Euratom that the IAEA inspectors will not be accompanied by Euratom inspectors.

The Lingen plant is inspected monthly by both Euratom and IAEA inspectors. These inspections are from one to two days duration and generally involve a records audit and what appears to be a partial verification of the in-process inventory. Pellet enrichments are checked by the Euratom inspector with a portable enrichment meter, selected rods are tested on the ENGmbH rod scanner against the Euratom standard rod, and occasionally pellet samples are taken.

The records are examined by Euratom and IAEA inspectors at the same time. The examination includes the main book (book inventory and master ledger), records of shipments and receipts, bundle assembly lists, and shipper/receiver differences.

For the monthly inspection of fuel rod production, the data for the last 24 hours of rod production are provided to the inspectors. The data list gives the rod serial number, enrichment, and UO₂ weight. The inspectors verify the serial numbers versus the list and select at random about five rods for scanning on the ENGmbH active rod scanner.

The plant inventory is verified once a year with both Euratom and IAEA inspectors present. Again, the Euratom inspectors play the lead role with the IAEA inspectors observing and witnessing the Euratom inspection activities.

The approximate number of man-days/year of inspection is about 50 for Euratom and about 40 for IAEA.

Verification Measurements

The methods used to verify inventory strata are given in Table 1.

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TABLE 1INSPECTOR VERIFICATION MEASUREMENTSAT EXXON NUCLEAR GmbH, LINGEN, WEST GERMANY

<u>Stratum</u>	<u>Measurement Methods</u>			
	<u>Item Count and ID</u>	<u>Weighing</u>	<u>NDA</u>	<u>Destructive Analysis</u>
Pellets in Shipping Boxes	Yes ⁽³⁾	Yes	Yes ⁽¹⁾	Yes
Pellets on Trays	Yes	Yes	Yes ⁽¹⁾	Yes
Rods	Yes	No	Yes ⁽²⁾	No
Bundles	Yes ⁽³⁾	No	No	No
Waste Barrels	Yes	No	No	No

(1) Pellet enrichments are verified using the Euratom inspectors' portable enrichment meter.

(2) Fuel rods are verified with the ENGmbH active rod scanner using a Euratom standard (PWR) rod.

(3) Packaged bundles and pellet boxes in shipping containers are excluded.

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For inventory verification, all inventory items, except packaged fuel bundles and packaged boxes of pellets in shipping containers are item counted on a 100 percent basis. Unpackaged fuel bundles are also item identified. Pellet trays are also checked on a sample basis for weight and item identification. Pellet samples are measured for enrichment and also sent to Karlsruhe, Germany for destructive analysis by Euratom and to Vienna, Austria for assay by the IAEA. Pellets stored on racks in shipping boxes are verified by 100 percent item count and re-weighed for gross weight and opened for pellet sampling on a fractional sampling plan basis. Fuel rods are 100 percent item counted and selected rods are measured on the ENGmbH active rod scanner versus a Euratom standard (PWR) rod. Also selected groups of rods are item identified. Waste barrels are item counted and item identified.

Verification Basis

The annual plant inventory verification is in conjunction with the plant physical inventory. The monthly inspections usually involve verification measurements and quantity estimations of the in-process inventory and production rates.

ENGmbH finishes its physical inventory prior to the arrival of the inspectors, and a computer-generated inventory list is available for the inspectors upon their arrival. This provides the inspectors with the required prior statement of the operator's inventory. The list is essentially complete. It has been reconciled and only small errors should remain. The Physical Inventory List (PIL) by batches is submitted to Euratom within 30 days.

Measurement quality is not directly evaluated. Accounting records are audited.

Material flow into or out of the plant is not verified; only records are audited. Any shipments or receipts during the annual inventory verification are subject to verification. However, it is not expected that this will occur and it has not to-date.

Impact on Production

The monthly inspections require no plant shutdown. For the operator's annual physical inventory taking and verification by Euratom, the plant is shut down for a week, usually during the summer vacation. A week is sufficient time for the operator to complete the physical inventory and for the inspectors to carry out their verification activities. The shutdown is optional and convenient; it is not mandatory.

Sampling

The formula for selecting sample sizes was not known by the Lingen operators. The goal quantity believed to be used in sample size selection is 75 kg U-235 with 0.95 believed to be the probability of including in the

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sample at least one falsified item if a diverter was to gain 75 kg U-235 contained by taking either whole or partial items. Samples are sent to Karlsruhe for analysis. IAEA pellet samples (usually of lesser number) are sent to Vienna.

NDA Equipment

The Euratom inspectors use their own portable enrichment meter for pellet verification. They use ENGmbH's rod scanner to verify rods. One Biblis (PWR) fuel rod is stored at the plant under Euratom seal to be used as the rod scanner standard. The IAEA makes no NDA measurements with IAEA equipment.

Cost

The cost of the inspection at Lingen has been very low, less than 0.1 percent of fuel assembly cost. Approximately 1 to 2 man-days per visit is expended by the plant operator. A half to one hour of rod scanning time is typical for the monthly inspections, a little longer for the annual verification. The inspection host, usually from the Plant Safeguards group, assigns technicians to escort and assist the inspectors, thus conserving engineering time.

Euratom pays for shipment of samples to Karlsruhe. The use of the rod scanner is also charged to Euratom, but actual payments are still being negotiated.

Information Reporting and Communication

Euratom reports to ENGmbH by letter after each monthly inspection. The report is merely a record of what was done and reports any abnormalities.

No measurement results are reported. The IAEA reports on the results of the inspection through Euratom, not directly. The information provided by Euratom reflects the results of the verification and contains other facts but does not provide any quantitative measurement results. Numbers of inconsistencies found are reported, but not identified. Those are discussed orally after the verification. Although the report states that the verification of the operator's physical inventory and monthly inspections were by the IAEA, it is to be understood that this is accomplished largely by observation of the Euratom verification activities.

Reporting to the IAEA by ENGmbH is also done through Euratom. Reports are similar to those in the U.S. - PIL, ICR's, Inventory Schedule, and Advance Notice of Receipts and Shipments. However, a Two-Year Production Forecast with expected receipts, fabrication and shipments is also required. No information is sent directly to the IAEA, nor do the IAEA inspectors contact the plant operator directly. The Lower Saxony Ministry concerned with Licensing, formally the Social Ministry (SM) but recently changed to the Ministry of State Affairs (MB), notifies ENGmbH when the inspectors are to arrive.

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Interface

The relationship between ENGmbH and the inspectors is non-adversarial. It is restrictive, however, in that little beyond that in the literal requirements of the Safeguards Agreement is provided.

Normally, the inspectors do not split up their work. Occasionally, an IAEA inspector has worked alone. But, generally, the IAEA inspectors only observe and witness the work of the Euratom inspectors. The latter make all direct measurements. It is not known whether sample selection is done jointly or not, as selection from the list provided is not done in the presence of the plant staff.

Euratom has about 120 inspectors. There are about 60 approved IAEA inspectors for nuclear facilities in Lower Saxony and no inspector is allowed to enter a plant unless he has been previously approved by the MB. The Federal Government receives copies of all reports.

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APPENDIX B

IAEA SAFEGUARDS AT SIMILAR FACILITIES

ASEA-ATOM LEU FUEL FABRICATION PLANT

IN VÄSTERÅS, SWEDEN

By

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Introduction

The purpose of this report is to describe the implementation of IAEA safeguards at the ASEA-ATOM's fuel fabrication plant in Västerås, Sweden. The plant is a medium-sized LEU conversion-fabrication plant which manufactures both BWR and PWR fuel.

Inspection

In Sweden, the safeguards inspections are performed by the Governmental Authority (Swedish Nuclear Power Inspectorate - SKI) and IAEA. Both carry out inventory verification and the routine inspections.

The ASEA-ATOM plant is inspected monthly by both inspectorates. The number of allotted IAEA man-days, at present 70 per year, is agreed upon between SKI and the IAEA and based on the present needs of the IAEA. The SKI, however, has general access to the plant. Usually, in connection with flow inspections, two inspectors from each inspectorate are present. The IAEA inspectors are always accompanied by the SKI inspectors.

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ASEA-ATOM's general ledger as well as related source data for the last period are audited. A portion of the material received during the period, including UF₆ cylinders, are check weighed and sampled.

At present, there are two physical inventory takings per year. More experience from the computerized safeguards system might give the possibility to reduce the physical inventory takings to one per year.

The needed shutdown time for an inventory taking is about one week.

Computer-generated inventory lists (by items) are provided to both inspectorates - a first edition before and a final after the inventory verification. The MBR and the PIL are sent within 30 days to the IAEA formally by SKI. Measurement quality is evaluated but at present not used for an overall estimation of measurement uncertainty on the facility level.

Impact on Production

The plant is shut down one month each year for vacation. Normally, just before or at the beginning of the vacation, one physical inventory is taken and verified by both IAEA and SKI.

There is, thus, ample time for the plant to remain shutdown for completion of the verification. This is at the option of the operator. However, with regard to timing and procedures to be followed this is subject to agreement with the SKI.

The verification usually takes 2-3 days. The second inventory taking, normally at the end of each year, is verified by SKI only. That verification takes 2 days.

Fraction of Inventory Included

The ASEA-ATOM plant is a full fuel fabrication plant receiving UF₆ as input material and shipping fuel assemblies. All UF₆ cylinders, except those sealed by the IAEA due to long-term storage, and 100% of UO₂ powder containers, pellet trays, fuel rods and fuel assemblies are subject to verification at the physical inventory taking.

The inventory of low level waste is low, since barrelled solid waste is shipped off-site for incineration and reclamation of uranium and filters are dissolved for reclamation of uranium. The conversion process is a precipitation process which is followed by a waste treatment process so that liquid waste discards are very low.

Sample Size and Goal Quantity

To estimate the sample size, a goal quantity of 75 kgs U-235 is used by the IAEA.

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The number of inventory verification samples taken is not a problem at ASEA-ATOM. The IAEA pays for all samples taken.

Verification Measurements

The methods used to verify each flow and inventory stratum are summarized in Table 1.

During physical inventory taking materials are not packed for shipping and are consequently available for verification.

Receipts are not held for the monthly inspection if they are needed for the production.

NDA Equipment

The inspectors do not use any of ASEA-ATOM's own NDA equipment. However, use of the rod scanner has been discussed.

Cost

ASEA-ATOM pays for 1983 a Safeguards fee of 880,000 SEK/year (ca \$120,000 at the current exchange rate) to SKI. The cost of ASEA-ATOM's manpower has not been accounted for, but probably lies in the range of one to two man-years per year. The IAEA pays at present for handling of nuclear materials by the operators to permit verification activities.

The cost of ASEA-ATOM escorts is not paid for. IAEA pays for cost of shipping samples to Vienna.

If one assumes that half the cost is associated with the SKI effort, the estimated IAEA burden is about 0.2% of the fuel fabrication cost. Thus, the operator's burden is small and about the same as in the U.S.

Information Reporting and Communication

Statements, in accordance with Article 90 in the Safeguards Agreement between Sweden and the IAEA, of inspections performed by the IAEA (annual and monthly) are reported in writing to SKI. SKI informs ASEA-ATOM by sending a copy of these Statements. ASEA-ATOM sends to the SKI Inventory Change Documents, which are source documents for the ICR, Advance Notice of Receipts and Shipments, and basic data for the PIL, and MBR reports. On basis of the national reporting system, these reports are provided to the IAEA by SKI. ASEA-ATOM does not send or receive any information directly from the IAEA, however, it is customary for the IAEA inspectors to discuss activities and findings with SKI representatives and the Safeguards Manager at ASEA-ATOM during an inspection.

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TABLE 1INSPECTOR VERIFICATION MEASUREMENTSUSED AT ASEA-ATOM LEU FUELFABRICATION PLANT IN SWEDEN

<u>Stratum</u>	<u>Item Count and ID</u>	<u>Measurement Methods</u>		
		<u>Weighing</u>	<u>NDA</u>	<u>Destructive Analysis</u>
<u>Flow</u>				
Receipts	Yes	Yes	No	Yes
Shipments	No ⁽¹⁾	No	No	Yes ⁽¹⁾
<u>Inventory</u>				
UF ₆ Cylinders	Yes	Yes	Yes ⁽²⁾	Yes ⁽³⁾
Pellets	Yes	Yes	No	Yes
Fuel Rods	Yes	No	Yes ⁽⁴⁾	No
Bundles	Yes	No	No ⁽⁵⁾	No

-
- (1) Pellets are sampled in connection with the rod loading. Fuel assemblies are counted and identified after the receipt at the power plants.
- (2) Enrichment measurement of UF₆ in cylinders is made using a Ge-detector and multi-channel analyzer.
- (3) Sampled at monthly inspection when a cylinder is not yet processed (vaporized) and in connection with the physical inventory verification.
- (4) Enrichments of fuel rods and active length are measured with a portable enrichment meter.
- (5) The neutron collar for verifying the fissile content of fuel bundles was used at the plant during calibration of the counter.

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Interface

The relationship between the operator, SKI and the IAEA inspectors is very good. The requests of the IAEA inspectors are normally considered reasonable. All IAEA proposals for changes in the Safeguards System are directed to and negotiated with SKI.

Requests by the IAEA regarding measures of an operational nature in the safeguards implementation are also directed to SKI, who after discussion will reject or agree to the proposed measures. This can take place anytime during an inspection.

APPENDIX C

EFFECTS OF NONMEASUREMENT ERRORS ON
AN LEU FUEL FABRICATION FACILITY MATERIAL BALANCE

CONTRACT NUMBER AC1NC108

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APPENDIX C

Effects of Nonmeasurement Errors on an LEU Fuel
Fabrication Facility Material Balance

John L. Jaech
October, 1984

Introduction

Nonmeasurement errors are those that occur whenever the results of a measurement process are not correctly recorded or reported, or whenever the measurement system produces a spurious result because it was not operating (or being operated) properly. It is noted that it is the origin of the error, and not the size, that distinguishes between a nonmeasurement error and a measurement error. However, from a practical viewpoint, it is normally the large nonmeasurement errors that are of interest in safeguards applications.

Errors are discovered in the course of an inspection or audit. Differences between tag values and remeasured values are generally classified as being due to errors of measurement as long as they are sufficiently small to be explainable based on criteria developed from the known measurement error parameters. An occasional small difference may be detected as being due to a nonmeasurement error in the course of the inspection if, for example, a mistake in transferring the source data to the item tag is noted. However, generally speaking, it is the large differences that are candidates for classification as being results of nonmeasurement errors.

This report focuses on the effect of nonmeasurement errors on a material balance from two perspectives: (1) What is the variance of the "difference" statistic? (2) How may the existence of such errors be factored in to the inspection design? The report applies the results of a recent revision to the IAEA Safeguards Technical Manual, Part F, Statistics, Volume 3 to a typical low enriched uranium fuel fabrication facility. For additional details on the results given here, see the following two sections of the reference document:

- 5.3 Effects of Mistakes and/or Defects: General Analysis of D and (MUF-D)
- 4.7 Inspection Planning Based on Estimation Sampling

The D* Statistic

The basis for the entire analysis is that the tag value (henceforth called the operator's value) has no assumed structure; it is merely a value assigned the item by the facility with no regards as to how it was assigned. This approach negates the need for classifying differences as

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being due to measurement errors, mistakes in reporting, or some other mechanism. Further, no knowledge of the operator's measurement system is required, and this is an important point because such information may be hard to obtain.

The "difference" statistic for this approach in which the operator's value is simply a declared value with no assumed structure is labeled D^* . This distinguishes it from the corresponding \hat{D} statistic derived from the assumption that the operator's value is a true value perturbed only by measurement errors. It is shown in the referenced Section 5.3 that in the event the operator's data reflect nothing but errors of measurement, then $(MUF-\hat{D})$ and $(MUF-D^*)$ have the same expected means and variances, although the expected variance of D^* is not the same as the expected variance of \hat{D} .

D_k^* for Stratum k, One Measurement Method

For simplicity in notation, the k subscript is not included.
Let

N = number of items in stratum

n = number of items inspected

n_c = number of items for which operator's data are corrected to agree with inspector's data

d_i = operator-inspector difference for item i ; $i = 1, 2, \dots, n$

$T = \sum_{i=1}^{n_c} d_i$ (renumbering the inspected items such that the first n_c are the ones corrected).

Then,

$$D^* = \frac{N}{n} \sum_{i=1}^n d_i - T \quad (1)$$

$$V(D^*) = \text{variance } D^* \\ = A_1 S_L^2 + A_2 \sigma_{\Delta}^2 + A_3 \sigma_{\epsilon}^2 \quad (2)$$

where

$$A_1 = \frac{N(n-n_c)[N(N-n+n_c)-2n_c(N-n)]+n_c(N-n_c)(N-n)^2}{n^2 N} \quad (3)$$

$$A_2 = \frac{N(n-n_c)[N(n-n_c)+2n_c(N-n)]+n_c^2(N-n)^2}{n^2} \quad (4)$$

$$A_3 = \frac{N^2(n-n_c)+n_c(N-n)^2}{n^2} \quad (5)$$

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$$s_L^2 = s_d^2 - \sigma_\epsilon^2 \quad (6)$$

$$s_d^2 = \frac{\sum d_i^2 - (\sum d_i)^2/n}{(n-1)} \quad (7)$$

σ_Δ = systematic error standard deviation for inspector

σ_ϵ = random error standard deviation for inspector

Note 1: The units of d_i , D^* , σ_Δ , σ_ϵ , and $V(D^*)$ are all the same: kg UO_2 , gU, lbs.U, etc.

Note 2: In the event $n_c = 0$, i.e., no items are corrected, then

$$A_1 = N(N-n)/n$$

$$A_2 = N^2$$

$$A_3 = N^2/n$$

Examples

Some typical examples for a medium throughput LEU fuel fabrication facility are given.

Example 1

Consider an inventory stratum of sintered pellets stored on pellet trays. The inspection consists of obtaining gross weights and comparing with the tag values. The parameters are

$$N = 1205 \quad n=82 \quad \sigma_\Delta = 4 \text{ g} \quad \sigma_\epsilon = 6 \text{ g}$$

The differences, d_i , in grams UO_2 are as follows. The items marked with asterisks are those whose weights are corrected to agree with the inspector's weights.

$d_i(\text{g } UO_2)$	frequency	$d_i(\text{g } UO_2)$	frequency
-185*	1	45	1
- 5	14	50	3
0	26	80*	2
5	19	90*	1
10	6	240*	1
15	3	260*	1
35	2		
40	2		82

$$\sum_{i=1}^{82} d_i = 1040 \text{ g } UO_2$$

$$s_d^2 = 2276.66 \text{ g}^2 UO_2$$

$$T = 565 \text{ g } UO_2$$

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$$D^* = \frac{(1205)(1040)}{82} - 565 = 14718 \text{ g } \text{UO}_2 = 12.967 \text{ kg U}$$

$$S_L^2 = 2276.66 - 36 = 2241 \text{ g}^2 \text{UO}_2$$

$$A_1 = 16,344.25$$

$$A_2 = 1,437,601$$

$$A_3 = 17,537$$

$$\begin{aligned} V(D^*) &= (16,344.25)(2241) + (1,437,601)(16) + (17,537)(36) \\ &= 60,260,412 \text{ g}^2 \text{UO}_2 \end{aligned}$$

$$\sqrt{V(D^*)} = 7.763 \text{ kg UO}_2 = 6.839 \text{ kg U}$$

$$D^* \pm 2 \sqrt{V(D^*)} = -0.711 \text{ kg U}; 26.645 \text{ kg U}$$

Example 2

Consider an inventory stratum of UO_2 powder. The comparison is on a gross weight of UO_2 basis.

$$N = 1662$$

$$n = 38$$

$$\sigma_\Delta = 10 \text{ g}$$

$$\sigma_\epsilon = 12 \text{ g}$$

d_i (g UO_2)	frequency	d_i (g UO_2)	frequency
- 860*	1	- 10	8
- 80*	1	- 5	1
- 70*	1	0	4
- 60*	2	35	1
- 50	1	20	1
- 40	3	15	1
- 30	2	10	2
- 20	9		
			<u>38</u>

$$\sum_{i=1}^{38} d_i = -1535 \text{ g } \text{UO}_2$$

$$s_d^2 = 19,234 \text{ g}^2 \text{UO}_2$$

$$T = -1130 \text{ g } \text{UO}_2$$

$$D^* = \frac{(1662)(-1535)}{38} + 1130 = -68266 \text{ g } \text{UO}_2 = -59.548 \text{ kg U}$$

$$S_L^2 = 19,234 - 144 = 19,090 \text{ g}^2 \text{UO}_2$$

$$A_1 = 70,606.25$$

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$$A_2 = 2,745,649$$

$$A_3 = 72,258$$

$$V(D^*) = 1.6328 \times 10^9 \text{ g}^2 \text{ UO}_2$$

$$\sqrt{V(D^*)} = 40.408 \text{ kg UO}_2 = 35.248 \text{ kg U}$$

$$D^* \pm 2 \sqrt{V(D^*)} = -130.044 \text{ kg U}; 10.948 \text{ kg U}$$

Example 3

Consider an inventory stratum of scrap materials. The comparison is on a gross weight of UO_2 .

$$N = 373$$

$$n = 8$$

$$\sigma_{\Delta} = 10 \text{ g}$$

$$\sigma_{\epsilon} = 15 \text{ g}$$

$$d_i \text{ (g UO}_2\text{)}$$

$$\begin{array}{r} -60 \\ -40 \\ -10 \\ 0 \end{array}$$

$$d_i \text{ (g UO}_2\text{)}$$

$$\begin{array}{r} 0 \\ 0 \\ 10 \\ 740^* \end{array}$$

$$\sum_{i=1}^8 d_i = 640 \text{ g UO}_2$$

$$s_d^2 = 71,686 \text{ g}^2 \text{ UO}_2$$

$$T = 740 \text{ g UO}_2$$

$$D^* = \frac{(373)(640)}{8} - 740 = 29100 \text{ g UO}_2 = 18.720 \text{ kg U}$$

$$S_L^2 = 71,686 - 225 = 71,461 \text{ g}^2 \text{ UO}_2$$

$$A_1 = 16,927.87$$

$$A_2 = 138,384$$

$$A_3 = 17,299$$

$$V(D^*) = 1.2274 \times 10^9 \text{ g}^2 \text{ UO}_2$$

$$\sqrt{V(D^*)} = 35.034 \text{ kg UO}_2 = 22.537 \text{ kg U}$$

$$D^* \pm 2 \sqrt{V(D^*)} = -26.355 \text{ kg U}; 63.795 \text{ kg U}$$

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Example 4

Consider an inventory stratum of UF_6 cylinders. The comparison is on a gross weight of UF_6 .

$$N = 11$$

$$n = 4$$

$$\sigma_{\Delta} = 650 \text{ g}$$

$$\sigma_{\epsilon} = 380 \text{ g}$$

$$d_i \text{ (g } UF_6)$$

$$\begin{array}{r} - 1000 \\ - 500 \\ 1000 \\ 1500 \end{array}$$

$$$$

$$$$

$$$$

$$\sum_{i=1}^4 d_i = 1000 \text{ g } UF_6$$

$$s_d^2 = 1,416,667 \text{ g}^2 UF_6$$

$$T = 0$$

$$D^* = \frac{(11)(1000)}{4} = 2750 \text{ g } UF_6 = 1.859 \text{ kg U}$$

$$S_L^2 = 1,416,667 - 144,400 = 1,272,267 \text{ g}^2 UF_6$$

$$A_1 = 19.25$$

$$A_2 = 121$$

$$A_3 = 30.25$$

$$V(D^*) = 7.9982 \times 10^7 \text{ g}^2 UF_6$$

$$\sqrt{V(D^*)} = 8.943 \text{ kg } UF_6 = 6.045 \text{ kg U}$$

$$D^* \pm 2 \sqrt{V(D^*)} = -10.231 \text{ kg U}; 13.949 \text{ kg U}$$

 D_k^* for Stratum k, Two Measurement Methods

In IAEA inspections, two measurement methods are generally used per stratum, one to detect gross discrepancies and the other to detect partial discrepancies and small biases. The two methods are often referred to as attributes and variables measurements respectively, but in fact, the attributes measurement method, although possibly rather crude, also often generates variables data such that a D^* statistic may be generated for both measurement methods. It is assumed that the items inspected by both methods form disjoint sets, i.e., no single item is inspected by both methods.

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To form the D^* statistic and calculate its variance in the case of two measurement methods, equations (1)-(7) are applied separately for each method, the only exception being that in applying (2), an average value is found for S_L^2 and used for both methods. Using the subscripts 1 and 2 for methods 1 and 2 respectively, the average S_L^2 is

$$S_L^2 = \frac{n_1 S_{L1}^2 + n_2 S_{L2}^2}{(n_1 + n_2)} \quad (8)$$

(In the referenced IAEA STM, a simple unweighted average is used, which is another possibility. Both estimates are unbiased).

Having found D_1^* , D_2^* , $V(D_1^*)$ and $V(D_2^*)$, the weighted average D^* for the stratum in question is

$$D^* = b_1 D_1^* + b_2 D_2^* \quad (9)$$

where

$$b_i = w_i / (w_1 + w_2) \quad ; i=1,2 \quad (10)$$

and

$$w_i = [V(D_i^*)]^{-1} \quad ; i=1,2 \quad (11)$$

The variance of D^* is

$$V(D^*) = (w_1 + w_2)^{-1} \quad (12)$$

Example 5

For a stratum of UO_2 powder, the following measurement methods are defined:

- Method 1: • Weigh the item, using assigned tare weight
• Use a nominal % U factor
• Use an enrichment meter (SAM-2) to measure the enrichment

- Method 2: • Weigh the item, empty the contents, and tare the container
• Sample the powder and analyze each sample for % U and % U-235

The parameters are

$$N = 1200 \quad n_1 = 25 \quad n_2 = 5$$

$$\sigma_{\Delta_1} = 425 \text{ g} \quad \sigma_{\Delta_2} = 15 \text{ g}$$

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$$\sigma_{\epsilon_1} = 170 \text{ g}$$

$$\sigma_{\epsilon_2} = 30 \text{ g}$$

where the error standard deviations include contributions from all identified error sources. The inspection data are:

Method 1 $d_i(\text{g U})$					Method 2 $d_i(\text{g U})$	
-2020*	216	314	406	607	-46	
-1189	220	337	469	617	24	
-106	224	361	495	620	6	
182	224	385	511	685	19	
184	281	398	589	1972*	-2	
$\sum_{i=1}^{25} d_i = 6982 \text{ g U}$					$\sum_{i=1}^5 d_i = 1 \text{ g U}$	
$s_d^2 = 469,804 \text{ g}^2 \text{ U}$					$s_d^2 = 773.20 \text{ g}^2 \text{ U}$	
$T = -48 \text{ g U}$					$T = 0$	
$D_1^* = \frac{(1200)(6982)}{25} + 48 = 335,184 \text{ g U}$					$D_2^* = \frac{(1200)(1)}{5} = 240 \text{ g U}$	
$s_{L1}^2 = 469,804 - 28,900 = 440,904 \text{ g}^2 \text{ U}$					$s_{L2}^2 = 773.20 - 900 = 0$	
Weighted average $s_L^2 = \frac{(25)(440,904) + 0}{30} = 367,420 \text{ g}^2 \text{ U}$						
$A_1 = 56,214$					$A_1 = 266,800$	
$A_2 = 1,435,204$					$A_2 = 1,440,000$	
$A_3 = 57,410$					$A_3 = 288,000$	
$V(D_1^*) = 2.8154 \times 10^{11} \text{ g}^2 \text{ U}$					$V(D_2^*) = 9.8611 \times 10^{10} \text{ g}^2 \text{ U}$	
$w_1 = 3.552 \times 10^{-12}$					$w_2 = 10.141 \times 10^{-12}$	
$b_1 = 0.259$					$b_2 = 0.741$	
$D^* = (0.259)(335,184) + (0.741)(240)$						
$= 86,990 \text{ g U} = 86.990 \text{ kg U}$						
$V(D^*) = (3.552 + 10.141)^{-1} \times 10^{12} = 7.303 \times 10^{10} \text{ g}^2 \text{ U}$						
$\sqrt{V(D^*)} = 270.241 \text{ kg U}$						
$D^* \pm 2 \sqrt{V(D^*)} = -540 \text{ kg U}; 714 \text{ kg U}$						

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D* over K Strata

With D^* having been calculated for each stratum in a material balance (or in one component of a material balance, such as an inventory component), then the overall D^* value is found by summing the individual strata D^* values, and affixing the proper sign, plus or minus. Specifically, letting D_k^* be the D^* value for stratum k ,

$$D^* = \sum_{k=1}^K A_k D_k^* \quad (13)$$

where $A_k = +1$ for beginning inventory and input strata and $A_k = -1$ for ending inventory and output strata.

The variance of D^* is found by summing over all strata $V(D_k^*)$, given by (2) or by (12) in the case of two measurement methods per stratum. In addition, the individual D_k^* values may be correlated if based on measurement methods that are common across strata. Methods for calculating the covariance are given in the referenced Section 5.3 of the IAEA STM.

However, when there are even a small number of nonmeasurement errors reflected in the data, the covariance terms are very small contributors to the total variance and may, for simplicity, be ignored. When there are no nonmeasurement errors, then one may use the \hat{D} statistic rather than the D^* statistic, and the formulas given in the STM for calculating the variance of \hat{D} already include the effects of the covariance terms. Thus, generally speaking, when using the D^* statistic, it is permissible to ignore the covariance terms. It is difficult to make precise probability statements about the material balance based on D^* anyway because of lack of knowledge about its probability distribution; inclusion of the covariance terms is a refinement generally not worth the effort.

Example 6

Consider the four strata of Examples 1-4, and find D^* and its standard deviation. The following table gives the results. $A_k = 1$ for all strata, these being inventory strata. All units are in kg U.

Stratum	D_k^*	$V(D_k^*)$
Pellets	12.967	6.839
Powder	-59.548	35.248
Scrap	18.720	22.537
UF ₆	1.859	6.045

$$D^* = 12.967 - 59.548 + 18.720 + 1.859 = 26.002 \text{ kg U}$$

$$\sqrt{V(D^*)} = [(6.839)^2 + \dots + (6.045)^2]^{0.5} = 42.821 \text{ kg U}$$

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Inspection Planning; Estimation Sampling

The current approach to selecting sample sizes in inspection planning involves performing a sufficient number of measurements with each method to detect gross and partial defects, and to result in a variance of \hat{D} sufficiently small to detect a specified bias in the facility data. Specifically, in a given stratum, the "attributes tester" (measurement method 1) performs a sufficient number of measurements to insure with probability $(1-\beta)$ that a gross defect will occur in the sample, the number of gross defects being M/\bar{x} , where M is the goal amount and \bar{x} the item average amount both expressed in the same units. The same type of criterion determines the sample size for the "variables tester in the attributes mode" (measurement method 2), the only difference being that now the defect size is $\gamma \bar{x}$ with $\gamma < 1$.

Without further discussion on this subject, the main point is that the sample size determination depends on the assumed strategy of the diverter, and on the desire to include in the sample any defects that exist in the population as a result of this strategy. "Detection" then consists of finding one or more such defects in the sample, and/or of having an \hat{D} value that differs significantly from zero, and/or of having a MUF value differing from zero. (The \hat{D} and MUF tests of significance may be combined in the MUF- \hat{D} test.)

In application, the occurrence of on or more "defects" in the sample does not result in "detection" in the sense that the material balance is declared unacceptable. Presumably, at some frequency of occurrence, this conclusion would be reached, but precisely where this point occurs is not defined. Rather, the evolving practice is to make some statement about the material balance even when defects or nonmeasurement errors, are discovered in the inspection, i.e., using the D^* statistic.

From this perspective, then, it would seem reasonable to design the inspection to result in a given variance of D^* , i.e., from an estimation sampling viewpoint. This is a difficult problem to address, but some preliminary results developed for a single stratum are helpful in providing a starting point.

First, from this perspective, both measurement methods produce variables type data so that a quantitative comparison can be made with the operator's data. The distinction is that the two methods differ in cost and in quality of the measurement. Measurement method 1 is less expensive and produces a less accurate and precise measurement.

Second, a diversion strategy must be defined because the variance of D^* is heavily dependent on S_L^2 which in turn is a function of the diversion strategy. If the diverter is perfectly free to create defects with no constraints, then his best strategy is to choose that set of defects which maximizes S_L^2 . He can make S_L^2 and hence the variance of D^* so large that it will be virtually impossible to make precise statements

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about the material balance. Realistically, some constraints must be placed on the diverter in the sense that some pattern of detected discrepancies should result in a conclusion that the inspection produced unacceptable results. Some work needs to be done in this area. (See the final paragraphs in the referenced Section 4.7 under Further Discussion.)

Third, it is pointed out that while discrepancies or nonmeasurement errors can be detected with either measurement method, if they are big enough, the primary purpose of making measurements with method 1 (the less expensive method) is to obtain in the sample enough such discrepancies that one can estimate S_L^2 and hence the variance of D^* . The principal role of measurement method 2 is to produce measurements of good quality in the absence of nonmeasurement errors such that the variance of \hat{D} (as opposed to D^*) is reduced below a certain level. From this perspective then, as is also true for the existing inspection planning approach, one makes many measurements with method 1 and few with method 2.

Computational Method 4.10 of the referenced Section 4.7 attempts to take into account the relative costs of performing measurements with each measurement method in determining an optimum plan. However, some experience is needed to see if this approach is feasible. For the present, Method 4.11 seems like a better starting point with Method 4.10 being a refinement that may have some later application. With this method, a total sample size is established and then $V(D^*)$ is calculated as a function of n_2 , the number of measurements performed by Method 2. A decision on n_2 and hence n_1 is then reached somewhat subjectively based on how rapidly $V(D^*)$ is reduced for a given increase in n_2 .

The first step is to determine a total sample size, $(n_1 + n_2)$. The current motivation is to ensure with probability $(1-\beta)$ that enough measurements are made to have at least one defect in the sample. Conservatively assuming that all defects are of size \bar{x} , the existing formula for n_1 is

$$n_1 = N \left(1 - \beta^{\bar{x}/M} \right) \quad (14)$$

For $\beta = 0.05$, this is essentially equivalent to requiring that an average of 3.0 defects would occur in the sample of size n_1 . To obtain a better estimate of S_L^2 , this average of 3.0 defects might well be increased, at the same time replacing n_1 in (14) by $(n_1 + n_2)$, the total sample size.

If the requirement is changed to require with probability 0.95 that a minimum of 3 defects of size \bar{x} would occur in the sample of size $(n_1 + n_2)$, then this is equivalent to requiring an average of 6.3 such defects. The sample size formula then becomes

$$(n_1 + n_2) = 6.3N\bar{x}/M \quad (15)$$

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The next step is to specify a diversion strategy for purposes of estimating S_L^2 . In a general sense, one can specify a family of such strategies by defining two parameters, λ and θ . Assume that the size of a discrepancy is uniformly distributed over the interval

$$\bar{x} (2\theta - \lambda) \text{ to } \lambda \bar{x} \quad (16)$$

$$\text{with } \lambda \leq 1 \text{ and } \theta \leq \lambda$$

The average discrepancy for a defected item is $\theta \bar{x}$ and hence the number of defected items is $M/\theta \bar{x}$. Note that if $\theta = \lambda = 1$, all items are defected by the maximum amount \bar{x} . If, for example, $\lambda = 0.5$ and $\theta = 0.2$, then the defected items range between $-0.1 \bar{x}$ and $0.5 \bar{x}$.

The quantity S_L^2 is a function of M , N , \bar{x} , θ and λ .

$$S_L^2 = \frac{M [N \bar{x} (\lambda^2 - 2\theta\lambda + 4\theta^2) - 3\theta M]}{3\theta N^2} \quad (17)$$

For $\theta = \lambda = 1$,

$$S_L^2 = M(N \bar{x} - M)/N^2 \quad (18)$$

The approach to estimation sampling within a given stratum is now illustrated with an example.

Example 7

Consider the stratum of UO_2 powder of examples 2 and 5 and assume that $\bar{x} = 17$ kg U and $M = 2500$ kg U. Say that in formulating the diverter's strategy, it is assumed that the maximum defect is $0.5 \bar{x}$ or 8.5 kg U, i.e., $\lambda = 0.5$. Further assume that 600 items are defected so the value for θ is found by solving

$$600 = \frac{2500}{17\theta}$$

$$\theta = 0.245$$

By (17)

$$\begin{aligned} S_L^2 &= \frac{2500[(1200)(17)(0.25 - 0.245 + 0.2401) - (0.735)(2500)]}{0.735(1200)^2} \\ &= 7.470 \text{ kg}^2 \text{U} \end{aligned}$$

Assuming $n_c = 0$ for both methods, from (2) and the data of Example 5,

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$$V(D_1^*) = 8964(1200-n_1)/n_1 + 260,100 + 41,616/n_1$$

$$V(D_2^*) = 8964(1200-n_2)/n_2 + 324 + 1296/n_2$$

From (11) and (12), the variance of D^* is

$$\begin{aligned} V(D^*) &= \left(1/V(D_1^*) + 1/V(D_2^*) \right)^{-1} \\ &= \frac{V(D_1^*) V(D_2^*)}{V(D_1^*) + V(D_2^*)} \end{aligned}$$

The value for $(n_1 + n_2)$ is, from (15)

$$\begin{aligned} n_1 + n_2 &= 6.3 (1200)(17)/2500 \\ &= 52 \end{aligned}$$

The following table then gives $\sqrt{V(D^*)}$ as a function of n_1 and n_2 .

n_1	n_2	$\sqrt{V(D_1^*)}$	$\sqrt{V(D_2^*)}$	$\sqrt{V(D^*)}$	$M/\sqrt{V(D^*)}$
49	3	687	1891	645	3.88
48	4	690	1637	636	3.93
47	5	693	1464	627	3.99
46	6	697	1336	618	4.05
45	7	701	1236	610	4.10
44	8	705	1156	602	4.15
43	9	709	1089	594	4.21
42	10	713	1033	587	4.26
41	11	717	985	580	4.31
40	12	722	942	573	4.36
...
35	17	748	790	543	4.60
...
30	22	782	693	519	4.82
...

One can argue that since $M/\sqrt{V(D^*)}$ exceeds 4 with $n_2 \geq 6$, 6 is an acceptable sample size. The decision as to the proper allocation of effort between Methods 1 and 2 is somewhat subjective.

The problem of planning for inspections from an estimation sampling viewpoint cannot be said to be solved. The inclusion of more than one stratum in planning has not yet been considered, nor has the feasibility of placing constraints on the divertor's strategy. The approach illustrated here can only be considered a starting point, and further study is needed.

END

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